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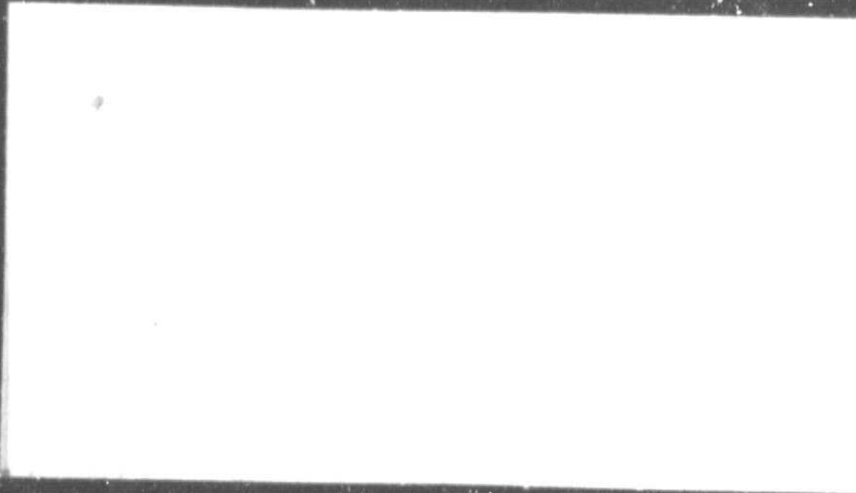
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SHORT RANGE WEATHER FORECASTING Final
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Utilization of Satellite Data and
Regional Scale Numerical Models in Short
Range Weather Forecasting
Final Report, NASA Grant No. NSG-5162

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**Utilization of Satellite Data and
Regional Scale Numerical Models in Short
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Abstract

This report summarizes conclusions of this study, including an evaluation of progress on this problem since the completion of this project five years ago.

It is concluded that overwhelming evidence has been developed in a number of studies of satellite data impact on numerical weather prediction that it is unrealistic to expect satellite temperature soundings to improve detailed regional numerical weather prediction.

It is likely that satellite data over the United States would substantially impact mesoscale dynamical predictions if the effort were made to develop a composite moisture analysis system. The horizontal variability of moisture, most clearly depicted in images from satellite water vapor channels, would not be determined from conventional rawinsondes even if that network were increased by a doubling of both the number of sites and the time frequency.

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B. Reprint of "Sensitivity of a mesoscale model to initial specification of relative humidity, liquid water and vertical motion. M. W. Kalb and D. J. Perkey. Seventh Conference on Numerical Weather Prediction, June 17-20, 1985.

Summary of Results.

The purpose of this project was to determine the usefulness of satellite sounding data in a research regional numerical weather prediction model. It was soon recognized that considerable experimentation and diagnosis would be required and that the bulk of the work would be in development of a quality software system. This effort was completed with development of the Limited-Area and Mesoscale Prediction System, LAMPS. The tests with satellite data included simulations of a cyclonic storm originally off the West Coast of the United States, 1200 GMT, 18 August, 1975.

The results of the tests comparing fine-mesh (140-km grid) simulations with and without the satellite sounding data showed relatively small impact with little benefit or harm. The signal to noise problem was highlighted when the differences between Goddard and Wisconsin retrievals had as large an impact as the difference between either of the above and the no satellite data case. When these results were presented in a seminar at Goddard Space Flight Center, it was suggested that the sounding data we got from Goddard must have used an obsolete retrieval system.

This conclusion is characteristic of most satellite data impact studies over the past 25 years. Any negative findings are based on obsolete techniques, by definition. Naturally, it always is hoped that the next test or the next retrieval system or the next satellite observing system will result in clear improvements in numerical weather prediction.

In any case, the computer software system did succeed and continues to serve the needs of many researchers at several institutions on several NASA projects (see Appendix A).

Current Status.

There have been extensive tests of many numerical models and many satellite data sets. There is no question that satellite data are of substantial help in large regions devoid of conventional sounding data. However, it is becoming practical to extend the conventional sounding data coverage to include most of the Northern Hemisphere oceans. It can be expected that continued advances in satellite data systems will result in their continued usefulness to supplement the ship-board sounding systems that are just now being implemented. The balance of this discussion will focus on the use of satellites in regions that have conventional sounding data.

Detailed numerical weather prediction models (regional and mesoscale models) have been in use by the research community for ten years. Nevertheless, it remains to be shown that mesh sizes less than about 80 km are worthwhile for operational weather prediction. The problem is that the phenomena that are really important to predict in detail cannot yet be predicted reliably. Our experience with LAMPS is in agreement with findings of other investigators.

The failure of mesoscale numerical weather prediction to reach operational weather prediction status can no longer be attributed to inadequate computer power. Whether it is inadequate initial data or inadequate model physics is still subject to debate, but our experience indicates that we are data limited. This conclusion is based on several cases of extremely good forecasts along with several cases of extremely poor forecasts. Since we don't know which forecasts to believe ahead of time, all forecasts are unreliable and operationally useless.

Much of our research into the problem of operational prediction, as opposed to scientific studies of weather system simulation, have dealt with heavy local rains or severe weather. In these situations it is critical to the users that the location of the event be determined within 100 km even though the timing of the threat is not that critical. The reliability of a forecast of hazardous weather should achieve at least one correct forecast for every two false alarms. Much of the damage from local flooding requires 12 hour advance notice. Many lives can be saved with much less notice if and only if an emergency response system is in place prior to the event, a requirement that is not practical if the events are too rare.

Substantial improvement in weather prediction during the past several decades have been directly related to improvements in numerical weather prediction made possible by the supercomputers now in use in all major prediction centers. Satellite data have been critical to success only for improvements beyond 36 hours and as a replacement for the weather ships and the reconnaissance aircraft in use 20 years ago. Geostationary satellite data are an integral part of severe convective storm forecasting but skill in this area still lags requirements by an unacceptable amount.

The challenge remains to effectively utilize satellites to improve short-range detailed prediction of hazardous weather in the United States, which in our experience is data limited. The key question is: are current satellite data systems adequate or must we wait for advanced satellite systems, including microwave sounders and lidar wind systems.

Our experience suggests that substantial gains in this problem area will not come from satellite temperature data but rather from satellite information on atmospheric moisture.

To date, little effort has been devoted to analysis of atmospheric moisture on the scales that are important to detailed numerical weather prediction. Such analyses would have to use geostationary images, VAS soundings, radar data and conventional surface and rawinsonde data in conjunction with a dynamical mesoscale prediction model with substantial moist physics. A man-machine four-dimensional data assimilation system would be required to perform the composite analysis.

The impact of moisture data is obvious in the sense that low-level atmospheric moisture limits many rainstorms. Also, clouds depend on moisture and clouds have a tremendous impact on boundary layer temperature and surface evaporation. However there is another impact that is both dramatic and unexpected. Precipitation is substantially enhanced when observed horizontal variations in water vapor are preserved, rather than smoothed, in the analysis stage even if the area-average water vapor is not changed. This phenomena was discovered by an experiment in which horizontal variations were artificially imposed but it was recently confirmed by an experiment in which realistic horizontal variations were removed by smoothing (see Appendix B).

Conclusion.

It is unrealistic to expect satellite temperature soundings to improve detailed weather prediction. It is likely that satellite data over the United States would substantially impact mesoscale dynamical predictions if the effort were made to develop a composite moisture analysis system. The horizontal variability of moisture, most clearly depicted in images from satellite water vapor channels, could not be determined from conventional rawinsondes even if that network were increased by a doubling of both the number of sites and the time frequency.

Appendix A

LAMPS PUBLICATIONS

a. Reports and Journal Articles

Perkey, D. J., and C. W. Kreitzberg, 1972: A one-dimensional numerical model to study the effects of cumulus clouds on the environment. *Drexel University Scientific Report No. 5, Project THEMIS*, Contract *F19628-69-C-0092, Dept. of Physics and Atmos. Sci., Drexel Univ., Philadelphia, PA, 100 pp. (AD760-123)

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SENSITIVITY OF A MESOSCALE MODEL TO INITIAL SPECIFICATION OF
RELATIVE HUMIDITY, LIQUID WATER AND VERTICAL MOTION

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1. INTRODUCTION

An often noted and lamented characteristic of numerical weather prediction models is that they require several hours to generate non-convective precipitation from a dry, synoptic-scale initial state. This "spin-up" time can be a serious drawback for limited-area mesoscale models which are run for relatively short time periods (<24 h). Thus, a significant portion (2 to 6 h) of a simulation may be consumed waiting for the model to generate internally consistent distributions of vapor water (q), cloud water (c), rain water (r) and vertical motion (w). Furthermore, because of the short time scales associated with mesoscale processes, after a model does finally generate precipitation in a given area, that precipitation is likely to be out of phase with reality. This situation limits the usefulness of mesoscale simulations for most operational purposes.

The purpose of this study is to investigate the relative importance of the initial specification of q, c, r and w for mesoscale precipitation forecasting. These four parameters were chosen because of their likely significance and obvious relationship to precipitation. Related initialization studies by others have also focused on some of these variables (Perkey, 1976; Tarbell, 1979; Perkey, 1980; Wolcott and Warner, 1981).

2. MODEL DESCRIPTION

The model employed for this study was the Drexel University LAMPS (Limited Area Mesoscale Prediction System) model (Perkey, 1976; Chung et al., 1981; Maddox et al., 1981). The LAMPS model is a 15-level, fully moist, primitive equation model with options for various grid spacing, and parasitic nesting of finer resolution simulations within coarser resolution simulations. A terrain following sigma-height coordinate is used in the vertical with levels at 0.0, 0.025, 0.375, 0.750, 1.25, 2.0, 3.0, 4.5, 6.0, 7.5, 9.0, 10.5, 12.0, 14.0 and 16.0 km.

The prognostic model variables include wind components u and v, virtual potential temperature θ_v , as well as q, c and r, and the modified Exner function π which is predicted at the model top and diagnosed hydrostatically at all lower levels. The vertical velocity is diagnosed from the continuity equation which is subject to the constraint that it equal zero at the model top and is determined by the terrain slope at the bottom. Horizontal space differencing is fourth-order accurate. Time differencing is second-order leapfrog with a weak time filter applied to avoid the inherent computational mode. A fourth-order diffusion term is applied to prognostic variables to eliminate features not resolvable by the model grid. The diffusion coefficient is increased near the lateral boundaries. Sponge boundary conditions are used in this study.

The planetary boundary layer is modeled with K-theory. Fluxes of moisture, heat and momentum through the surface layer are handled with Monin-Obukhov similarity. Precipitation is partitioned into grid resolved and parameterized modes which incorporate Kessler type parameterization for microphysical conversions among q, c and r. Only the grid-scale precipitation processes were invoked for this study.

Model simulations were performed on a 70-km mesh over an area bounded by 107° and 80° W longitude and 23.625° and 43.625° N latitude. In diagnostic portions of this paper we will focus on a subset of this domain.

3. EXPERIMENTAL DESIGN

The basic experimental strategy can be summarized as a four step process. First, a control initial state is derived from a "reference simulation" which already contains significant mesoscale structure and precipitation (see below for discussion of the reference simulation). Second, a control simulation initialized with the control initial state is run. Third, various sensitivity simulations, each initialized with a different degraded version of the control initial state, are run. Finally,

conclusions are drawn based upon the degree to which each sensitivity simulation reproduces the control. Differences between the sensitivity and control simulations are attributed to specific alterations of the control initial state. The experimental design is shown schematically in Figure 1.

The reference simulation was a 16-h LAMPS simulation beginning at 1200 GMT 6 March 1982. It was initialized with zero cloud and rain water and with non-divergent winds prescribed from a non-linear balance equation; thus, initial vertical motion was zero. The reference simulation serves as surrogate or laboratory analog to the real atmosphere. Even though all conclusions are drawn within the context of a numerical model representation of the atmosphere, a highly verifiable reference simulation (see Section 4 below) lends credibility to projecting results of this study to the real world. Internally and dynamically consistent fields of u , v , θ , τ , q , c and r eight hours (2000 GMT) into this reference simulation were selected as the mesoscale control initial state. Although other variables like pressure tendencies and diabatic heating rates were available, only the seven basic variables listed above were used since, with the exception of liquid water variables, they represent the variables that are measured by synoptic-scale conventional observing networks and are traditionally used to initialize numerical models.

This control initial state is interpreted as corresponding to a "perfect" mesoscale specification of the standard meteorological variables (u , v , T , q and p) as well as c and r which have been added for these experiments. Because the wind and mass fields are dynamically consistent with the model representation, the simulations initialized at 2000 GMT do not experience deleterious effects from geostrophic adjustment processes. The control and sensitivity simulations ended at 0400 GMT 7 March, their length being limited because the model precipitation, the main focus of this study, began to move out of the model domain.

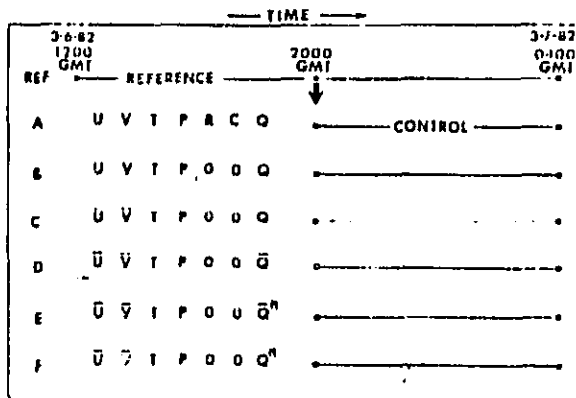


Figure 1. Schematic summary of model simulations. Experiments are listed vertically along with the state of the initial variables. The duration for each simulation is indicated by horizontal time lines. An overbar superscript denotes smoothing. An "R" superscript indicates moisture fields which have been reduced to be sub-saturated.

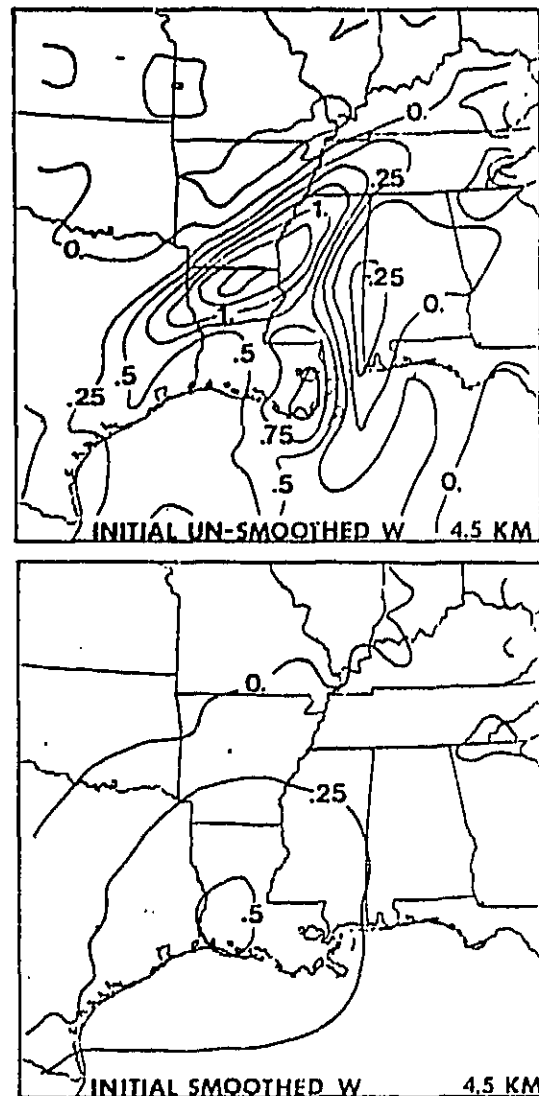


Figure 2. Initial (2000 GMT) vertical motion fields at 4.5 Km resulting from unsmoothed (upper panel) and smoothed (lower panel) horizontal wind fields. The contour interval is 0.25 cm s^{-1} .

Only the control simulation and five of 15 sensitivity simulations are described in this paper. Initial conditions for Simulations A through F are summarized in Figure 1. The control simulation is designated A. The initial state for Simulation B was identical to A except that cloud and rain water were initialized to zero. In addition to $c = 0$ and $r = 0$ in Simulation C, the horizontal wind fields were smoothed to reduce the vertical vorticity to those that could be considered representative of synoptic-scale vertical motions. In Simulation D the initial specific humidity field, q , was also smoothed such that small-scale structure was reduced while conserving the total precipitable water within the domain. Simulation E is the same as D except that the specific humidity was reduced in areas where relative humidity exceeded 90%. The relative humidity and subsequently the q field were altered according to

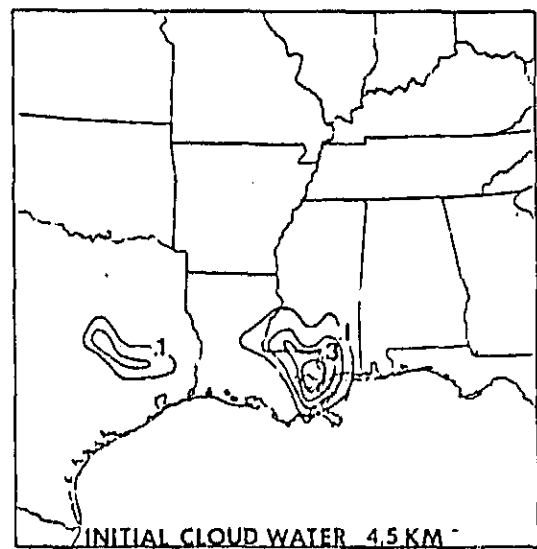
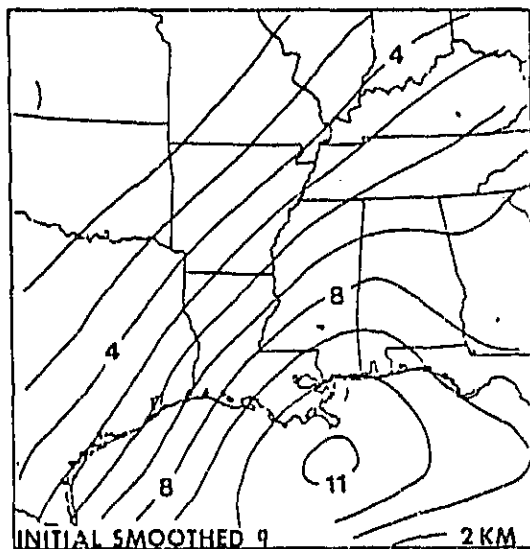
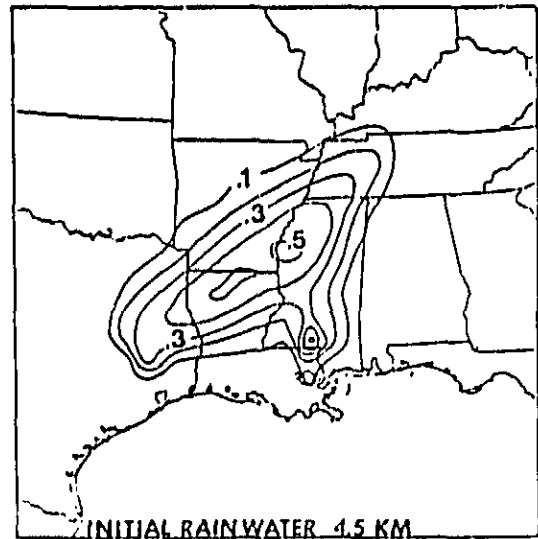
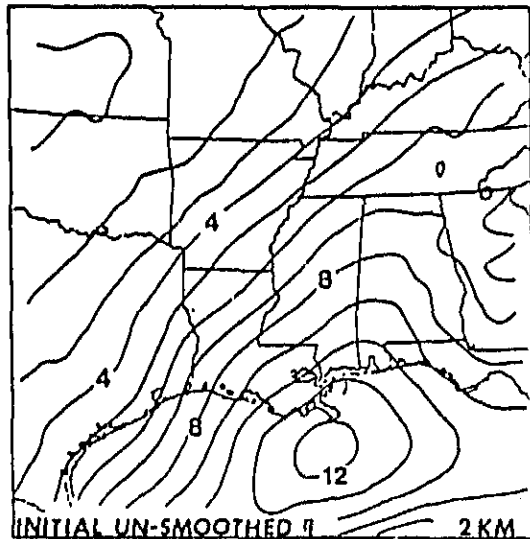


Figure 3. Initial smoothed and unsmoothed specific humidity fields at 2 Km. Units are gm Kg^{-1} .

Figure 4. Rain and cloud water at 4.5 Km in the control initial state at 2000 GMT. Units are gm Kg^{-1} with a contour interval of 0.1.

$$\text{RH}^* = \text{RH} - (\text{RH} - 90)/2$$

Thus, areas of 100% RH were reduced to 95%. Simulation E is a more severe constraint on the water vapor distribution than Simulation D. This simulation was suggested by the common occurrence that an objective analysis of RH at a given point, being a weighted sum of surrounding observations, may produce an RH value well below 100% when only one or two observations over a large domain indicate saturation. While the Control Simulation A represents a perfect mesoscale initialization, Simulation E is intended to correspond to model results obtained using standard, large-scale initialization data and procedures. In Simulation F, humidity was reduced but no smoothing was performed.

Figures 2 and 3 illustrate the effects of smoothing the horizontal wind fields on the resulting vertical motion field and of smoothing the specific humidity field that comprise Simulations B through E. Figure 4 shows the distributions of cloud and rain water present in the control initial state.

4. COMPARISON OF THE REFERENCE SIMULATION TO OBSERVATIONS

To establish credibility for the reference simulation from which all initial data were derived, those results are compared briefly to observations. In Figures 5 and 6 500-mb height fields at the beginning and end of the simulation show the correct changes in trough locations and orientations. Differences in the initial model and observed 500-mb height fields

are primarily because the observed field was hand-drawn based on available radiosonde data while the model initial field was based on the same radiosonde data, but objectively analyzed using LPM analyses for first guess fields.

Satellite IR images (Figure 7) depict primary cloud/precipitation areas for the case study period. The images have been enhanced so that white areas correspond to cloud top temperatures less than 232 K. The three-hourly sequence starts at 1200 GMT 6 March and ends at 0300 GMT 7 March close to the end time of the model simulation. There are a number of important features to be noted. First, the initial mesoscale cloud pattern is dominated by a SW to NE band extending from eastern Texas to Missouri and by a large precipitation area in Illinois and Indiana. This band travelled eastward and became a secondary feature, giving way to a rapidly developing cloud/precipitation system on the Louisiana coast between 1500 and 1800 GMT. This developing area expanded rapidly northward as it propagated toward the east-northeast. During this period the 500-km wide system engulfed most of Mississippi, then Alabama and then Georgia by 0300 GMT. Notice that by 0000 GMT another band has developed in eastern

Louisiana and Arkansas and moved northeastward reaching Indiana and Ohio by 0900 GMT (not shown).

All of the above features were seen to evolve in the model simulation. Because space does not permit lengthy map sequences only three figures are shown to highlight the model evolution and verification. The initial formation of accurate clouds and precipitation patterns did not occur until about 1800 GMT and were first evident as diabatic (latent) heating rates (Figure 8a). The correspondence of this figure to the 1200 GMT satellite images is excellent; however, the model was nearly 6 h late in producing liquid water. Thus, the reference simulation is a perfect example of the time delay between precipitation initiation in mesoscale models and reality discussed in the introduction. By 2100 GMT rain had reached the surface and precipitation rate fields (Figure 8b) show the development of the precipitation area on the Louisiana coast. This field shows excellent correspondence to the 1800 GMT IR image, so that the model appears to be "making up" for the initial delay. By 0100 GMT rain water at 4.5 km (Figure 8c) shows that model precipitation has nearly caught up with observations. In particular, note the correspondence of the main

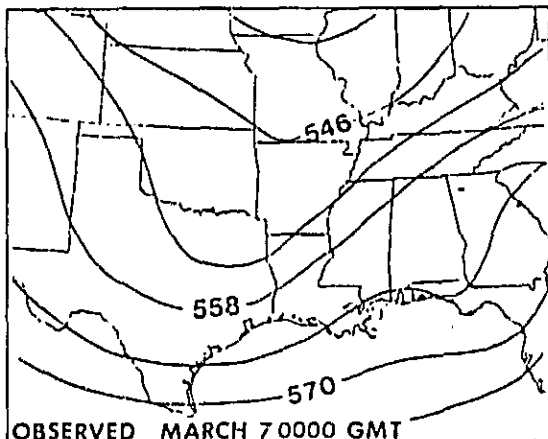
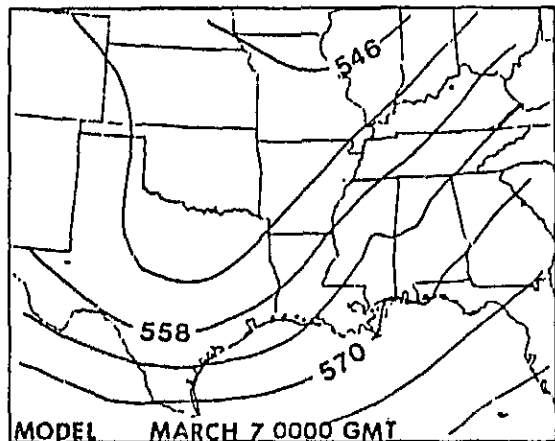
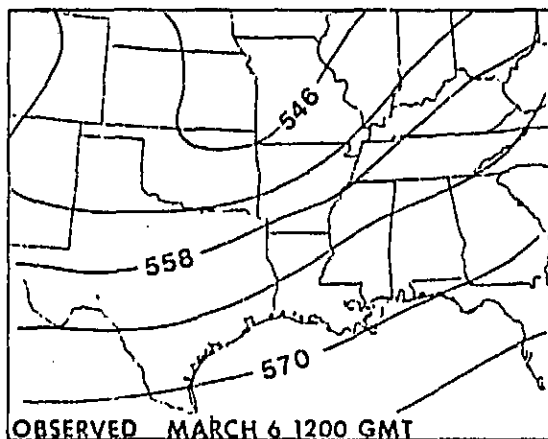
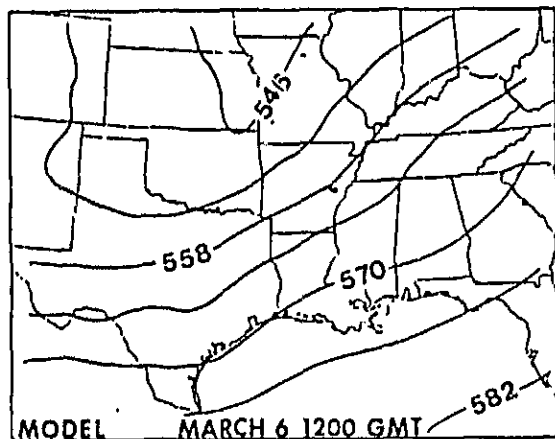


Figure 5. Model 500 mb geopotential height analyses for the reference simulation initial state and twelve hours later. Contours are labelled in dekameters.

Figure 6. Observed 500 mb geopotential height analyses corresponding to the model analyses in Figure 5.

precipitation area over Alabama and development of the second precipitation band over eastern Louisiana with the 0000 GMT satellite image. The model secondary band propagated toward the northeast as observed.

Based upon this brief comparison between major mesoscale precipitation structures in the model and observations, the reference simulation appears to provide a reasonable and accurate analog to the evolution of the real atmosphere for 6-7 March, 1982.

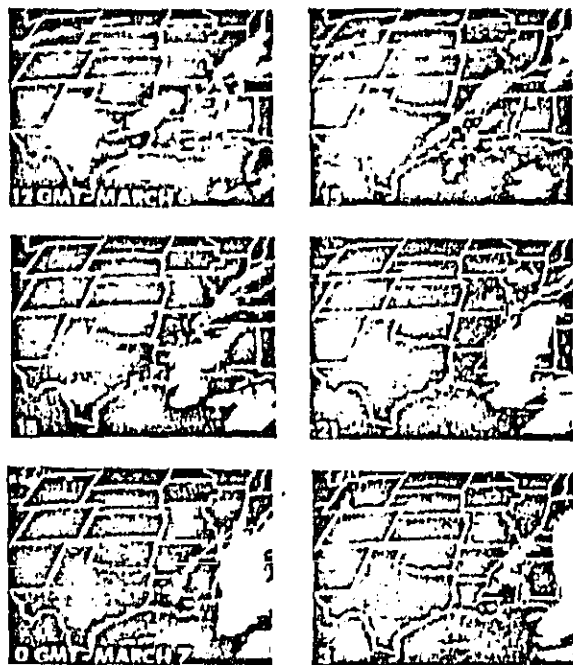


Figure 7. Time sequence of satellite infrared images corresponding to the period covered in the model reference simulation. Images were enhanced so that brightness temperatures less than 232 K appear white.

5. RESULTS OF THE SENSITIVITY SIMULATIONS

In this section precipitation for Simulations A through F are compared. All calculations were made for a subset or "window" of the model integration domain. This window encompasses the main precipitation areas at all times (the window boundaries are 28° to 42° N, 82° to 98° W). Total precipitation values, plotted against time in Figure 9, were calculated by integrating half-hourly surface accumulations (mm) at all grid points within the window. The Control Simulation A produced the most precipitation at nearly all times. Neglecting c and r (Simulation B) reduced the total area integrated precipitation by only a few percent by the end of the simulation; however, more significantly, neglecting c and r caused a delay in the appearance of significant

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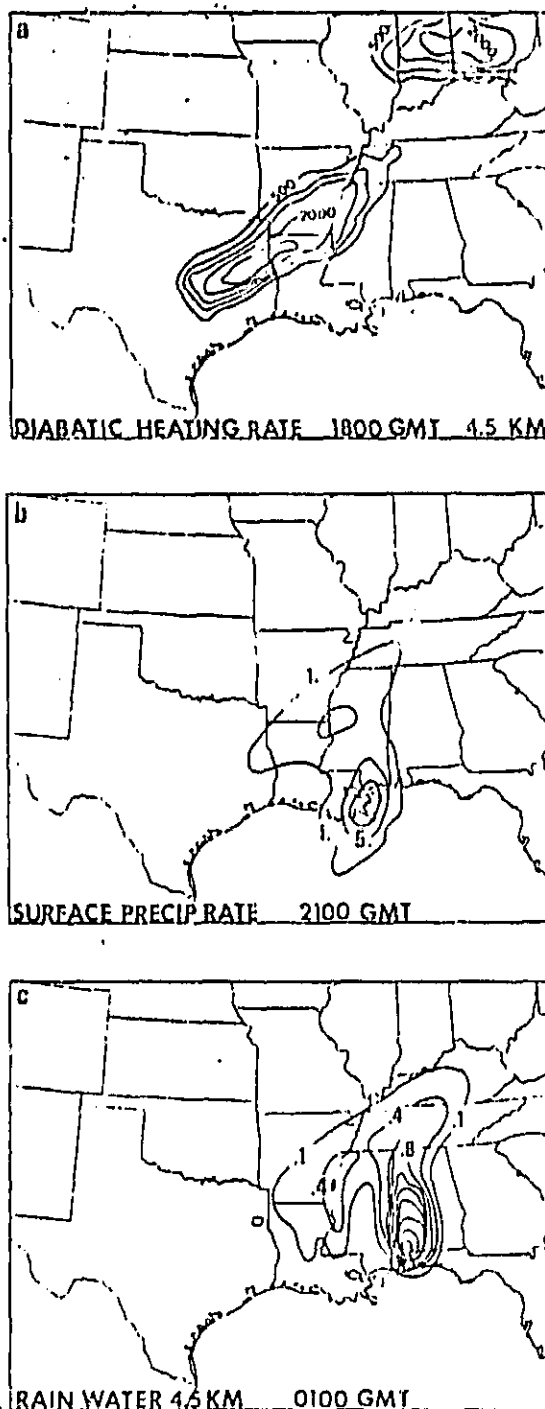


Figure 8. Fields of a) diabatic heating rates (units $10^{-4} \text{ J Kg}^{-1} \text{ s}^{-1}$), b) surface precipitation rates (units $10^{-4} \text{ mm s}^{-1}$) and c) rain water at 4.5 km (units gm Kg^{-1}) at several times in the reference simulation. These are to be compared with satellite images in Figure 7.

surface precipitation (defined by total precipitation >100 mm) by about $1\frac{1}{2}$ h relative to the control. Smoothing the wind fields (Simulation C) extended this delay by an additional $1\frac{1}{2}$ h and slightly reduced the total precipitation below that in Simulation B.

The most critical factor was the representation of the initial moisture analysis (sensitivity simulations D through F). The degree of smoothing indicated by Figure 3 resulted in a 44% reduction as compared to the control at 0400 GMT (curve A versus D). Ensuring nonunsaturation before smoothing (Simulation E) netted a 55% reduction in total precipitation and a $2\frac{1}{2}$ h delay before significant precipitation occurred. Notice that Simulations D and E, both of which used smoothed initial moisture fields, continuously diverge from the control curve indicating that model precipitation was unable to recover from changes introduced by the moisture smoothing. This impact may be related strongly to the amount of detail in the initial state (E versus F).

From Simulations D and E alone it is not possible to assess the relative impact of smoothing versus reducing saturated areas to 95% RH. Smoothing not only eliminates small-scale structure but also reduces the amount of area experiencing initial saturation; thus, Simulations D and E are not mutually exclusive in their specification of moisture.

Simulation F reduced the relative humidity but performed no smoothing. Thus, the degree to which F produces less precipitation than C is because the initial state is unsaturated. The influence of smoothing is assessed by the difference between F and E. Simulation D shows the effect of smoothing without regard to saturation in the initial state.

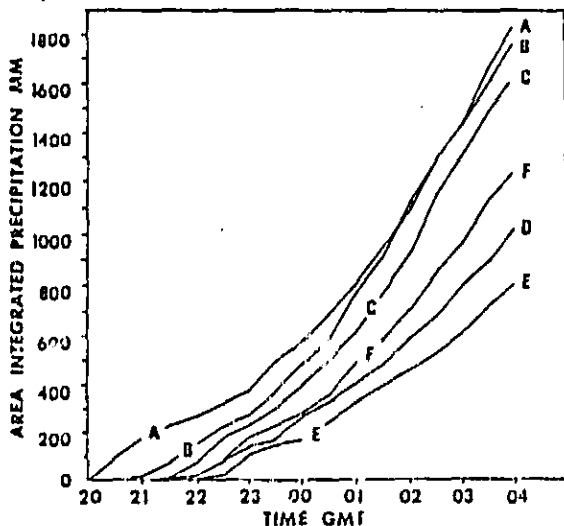


Figure 9. Area integrated precipitation as a function of time for the control and sensitivity simulations. Line A corresponds to a "perfect" mesoscale initialization while line E represents model initialization from conventional synoptic scale observations.

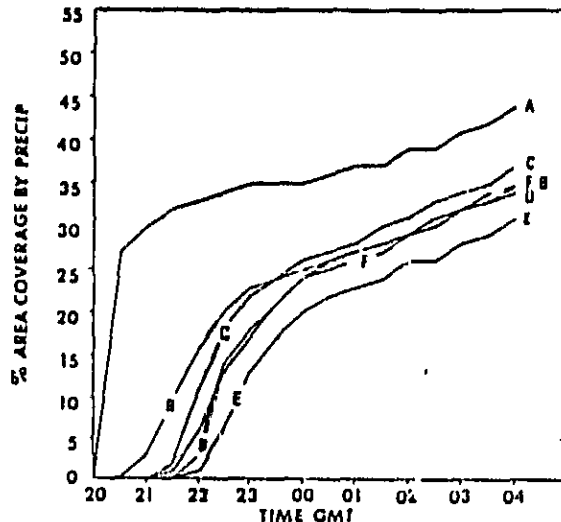


Figure 10. Percent areal of model domain window receiving precipitation at the surface for the same cases as in Figure 9.

Percent areal coverage of precipitation within the window is displayed as a function of time in Figure 10. Using 10% coverage as a reference point, it is seen that, again $1\frac{1}{2}$ h is required for the dry (no liquid water) Simulation B to reach the same level as the control simulation. For 20% coverage the delay is $2\frac{1}{2}$ h. Smoothing the initial humidity and vertical motion fields as in Simulation C contributes another $1\frac{1}{2}$ h to the delay for 10%. Degrading the representations of q , c , r and w all result in reduction in the total area affected by precipitation, and all remain 10 to 15% below the control simulation showing no evidence of recovery beyond the initial spin-up period.

Figures 11 and 12 compare distributions of rain water at 4.5 km and total surface accumulations for Simulations A and E at 0400 GMT, respectively. These simulations were chosen to represent opposite ends of the spectrum for mesoscale initialization of q , c , r and w . In the control simulation, the large precipitation area had three distinct centers: one over southeast Alabama, one over central Tennessee and a weak one over northeastern Kentucky. The degraded Simulation E shows one rain water (Figure 11) maximum in central Alabama with the largest value being 1.62 g kg^{-1} compared to 3.46 g kg^{-1} for the control.

Both simulations show the same pattern for total accumulation although the maximum for the control is almost four times as large as that for Simulation E. Part of this difference must be due to the several hour spin-up time for precipitation in E. Similar maps for the other simulations indicated that degradation of the initial c , r and w fields resulted in only minor changes in precipitation patterns and accumulations, i.e., these simulations converged toward the control simulation as suggested in Figure 9 for area integrated precipitation. Thus, again the largest effects resulted from degradation of the q field.

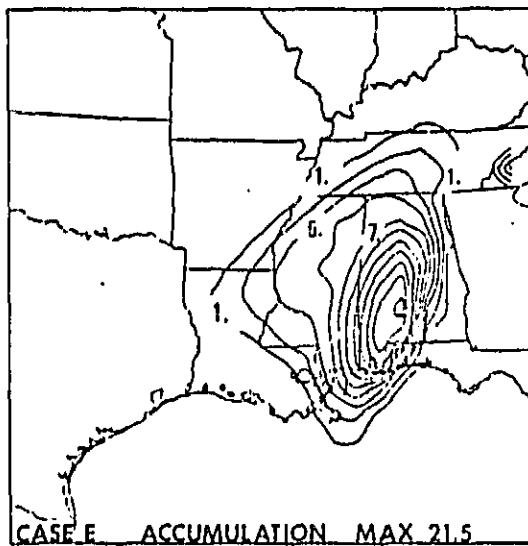
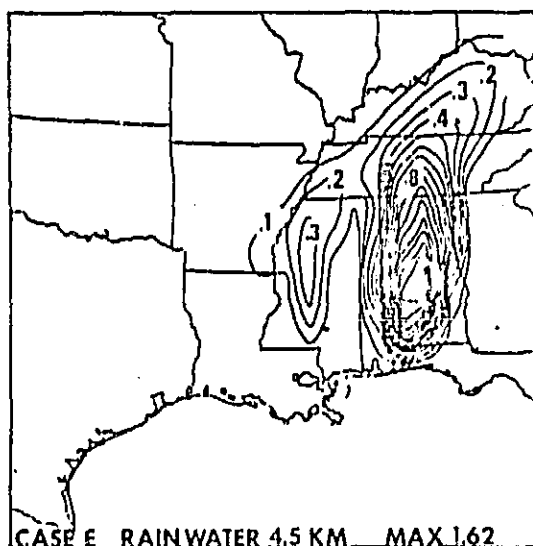
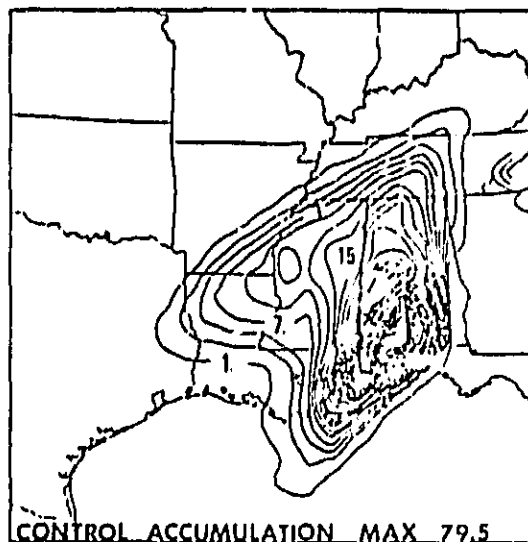
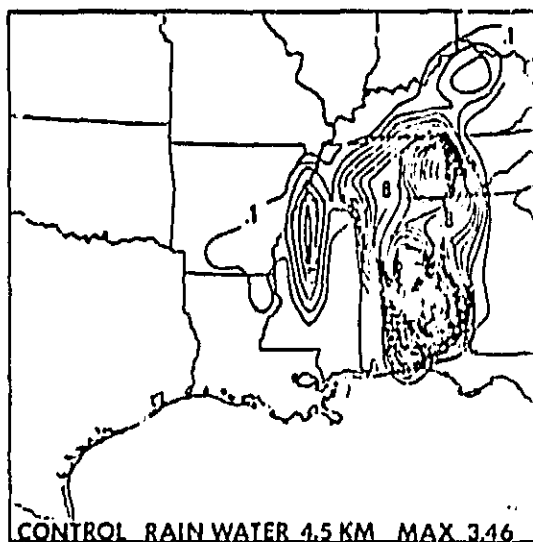


Figure 11. Distribution of 4.5 Km rain water at 0300 GMT for the control simulation A (upper panel) and simulation E (lower Panel). Contour interval is 0.1 gm Kg^{-1} .

Figure 12. Model surface precipitation accumulations through 0300 GMT for the control simulation A (upper panel) and simulation E (lower panel). Contour interval is 2.0 mm.

6. CONCLUSIONS

This study attempted to estimate the degree to which the synoptic-scale (as opposed to a mesoscale) initial state limits the accuracy of mesoscale numerical model simulations of precipitation. Results from these simulations with the LAMPS mesoscale model for one case suggest that failure to provide accurate mesoscale initial fields of water vapor and vertical motion, and initial cloud and rain water fields causes substantial modification to both the areal coverage and total rainfall amounts calculated by the mesoscale model. Mis-specification of these key parameters is sufficient to account for the several hours

commonly required to spin up precipitation in mesoscale numerical simulations. Recall that the initial mesoscale temperature and pressure distributions were not modified in these simulations.

It was found that, although cloud and rain water were not essential for reproducing the total amount of surface precipitation after the first several hours, neglecting c and r in the initial state did result in a 2-h delay in generating basic precipitation patterns. The primary effect of initializing the model with synoptic-scale vertical motions (instead of mesoscale) was to increase this time delay between model initialization and initial generation of surface precipitation.

Alteration of the mesoscale initial moisture fields had the greatest impact. Smoothing the moisture field resulted in smaller total accumulation and areal coverage of precipitation. The effects of smoothing were two-fold. About half of the model impact was because smoothing reduced the areas experiencing saturation. The other half resulted from the elimination of small-scale structure in the moisture field. The latter is consistent with LAMPS experiments shown by Perkey (1980) in which random perturbations were added to a smooth initial moisture analysis while conserving the total amount of water vapor. In that study it was found that the model mesoscale precipitation structure and characteristics were highly sensitive to the amount of detail in the initial moisture analysis. The present study corroborates those conclusions but is more poignant in that the initial states did not rely on a statistically perturbed moisture field but were deterministic and could be linked to real mesoscale precipitation episodes.

It must be emphasized that the degraded initial states of Simulations B through F are only superficially analogous to synoptic-scale conditions because the usual difficulties with data sampling, measurement error, and objective analysis error have been eliminated in these idealized simulations. Since the mesoscale temperature and pressure fields were retained, this suggests that the present study probably still overestimates current capabilities for producing accurate mesoscale precipitation forecasts utilizing conventional data sources.

7. ACKNOWLEDGEMENTS

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